Few-Body Syst 55:639–644
DOI 10.1007/s00601-014-0841-3

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Investigation of the Three-Nucleon System Dynamics in the Deuteron–Proton Breakup Reaction

Received: 29 October 2013 / Accepted: 1 February 2014 / Published online: 19 February 2014

Abstract Precise and large sets of cross section, vector A_x, A_y and tensor A_{xx}, A_{xy}, A_{yy} analyzing power data for the ${}^1H(\mathbf{d}, pp)n$ breakup reactions were measured at 100 and 130 MeV deuteron beam energies with the SALAD and BINA detectors at KVI and the Germanium Wall setup at FZ-Jülich. Results are compared with various theoretical approaches which model the three-nucleon system dynamics. The cross section data reveal a sizable three-nucleon force (3NF) and Coulomb force influence. In case of the analyzing powers very

This work was supported by the Foundation for Polish Science—MPD program, co-financed by the European Union within the European Regional Development Fund, Małopolskie Centrum Przedsiebiorczości—Project “Doctus-Małopolski fundusz stypendialny dla doktorantòw”, the Polish 2013-2015 science founds as research Project No. 2012/05/E/ST2/02313 and funding from Jagiellonian University within SET project—the project is co-financed by the European Union.

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low sensitivity to these effects was found and the data are well describe by 2N models only. For A_{xy} at 130 MeV, serious disagreements were observed when 3NF models are included in the calculations.

1 Introduction

One of the key issues of modern nuclear physics is the investigation of the forces acting between nucleons. Properties of three-nucleon (3N) systems at medium energies are determined by the pairwise nucleon–nucleon (NN) interaction, which is a dominant component. The interaction models are created based on the meson exchange theory or phenomenology. These so-called realistic NN potentials, like CD Bonn, Nijmegen or Argonne AV18 are able to predict observables for 2N systems with very high precision. To test thoroughly these models, systems with more than just two nucleons are needed. The simplest is the 3N system, which can be used to test dynamics and features of the 3N Hamiltonian. Such systems can be studied in details with the use of the deuteron breakup reaction, offering a very unique laboratory in which even very subtle dynamical effects like the 3NF, Coulomb force or relativistic components can be studied.

The theoretical predictions of observables are nowadays obtained via exact solutions of the 3N Faddeev equations for the given interaction model, like for example realistic NN potentials supplemented with 3NF models (TM99 3NF [1] or Urbana IX 3NF [2]), or the 3N system dynamics is treated within the coupled-channels (CC) approach [3] with a single Δ-isobar degree of freedom (d.o.f.), which generates also certain 3NF effects. Another alternative way comes from chiral perturbation theory (ChPT) where the nuclear potential is obtained by a systematic expansion in terms of momenta, and the many-body interactions appear naturally at increasing order. The non-vanishing 3NF enters at the next-to-next-to-leading (NNLO) order [4,5], which is numerically fully developed. Within the CC formalism the Coulomb interaction was implemented into the calculations for the first time [6]. Recently, a consistent theoretical treatment of a phenomenological 3NF and the Coulomb force has been achieved also for the AV18+UIX potential [7] that allows to investigate the role of both effects to a high level of accuracy. Moreover, the relativistic treatment of the breakup reaction in the 3N system was developed for calculations using the NN potential [8] and this approach has been also extended to calculations including the 3NF [9]. To verify the model predictions, the deuteron breakup reaction can be used as a valuable experimental tool. The final state of the reaction is complex enough to test different ingredients of few-nucleon system dynamics, which enter with varying strength in certain phase-space regions. The extensive and precise data sets which were obtained in a series of new generation experiments are used to distinguish between different interaction contributions and to test the corresponding predictions.

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2 Experimental Setups

The $^1H(\mathbf{d}, pp)n$ breakup reactions were studied in different phase-space regions with the use of three detection systems: the SALAD [10] and BINA [11] at KVI and the Germanium Wall (GeWall) [12] at FZ-Jülich. Results of the analyzing powers were obtained with the BINA and SALAD detectors at polarized deuteron beam energies of 100 [13] and 130 MeV [14], respectively. The cross-section data [15,16,18–20] were measured using the SALAD and GeWall detectors at a deuteron beam energy of 130 MeV. The BINA detector offered access to almost the full phase-space, whereas the SALAD and GeWall setups covered only forward polar angles.

The SALAD detector consisted of a three-plane multi-wire proportional chamber (MWPC) and two layers of a segmented scintillator hodoscope: horizontal ΔE and vertical stopping E detectors. The acceptance of the setup covered the region of polar angles from 12° to 40° and the full range of azimuthal angles. The liquid hydrogen target was placed inside the scattering chamber. The BINA apparatus was constructed as an upgraded version of SALAD and possessed two main parts called Wall and Ball. The Wall inherited most parts and features from SALAD, covering the same angular range and built of the same MWPC and modified ΔE and E hodoscopes. The backward part is ball-shaped and consists of 149 phoswich detectors which cover polar angles between 40° and 160°. The Ball plays two roles: particle detector and scattering chamber. In the measurements a liquid target (LH_2) was used.

The GeWall setup at the Research Center in Jülich (FZJ) consisted of three high-purity semiconductor position sensitive germanium detectors. Two different types of the detectors were used: a thin transmission detector "Quirl" with excellent spatial resolution to determine the position and energy loss (ΔE detector) of the passing charged particles, and two thick energy detectors E1 and E2 with excellent energy resolution. The angular acceptance of the apparatus was 5°–14° for the polar and 2π for the azimuthal angles.

3 Results

In order to search for subtle dynamical effects in few-body systems a precise and systematic database is necessary, making measurements very demanding. Our new-generation experiments fulfilled these conditions and provided a very rich set of differential cross-section, vector A_x, A_y and tensor A_{xx}, A_{xy}, A_{yy} analyzing power data for the breakup reaction. The cross-section data were obtained for about 80 [15–17] and 145 [18–20] geometries, defined by the polar angles of the two outgoing protons, θ_1, θ_2, and their relative azimuthal angle φ_{12} for an energy of 65 MeV/nucleon. The vector and tensor analyzing power data were measured in 90 geometries for each of the tensor and vector analyzing powers [14] with the SALAD detector. Moreover, measurements with BINA and GeWall delivered additional sets of data for vector analyzing powers at deuteron beam energies of 100 MeV [13] and 130 MeV [12], respectively.

The cross sections obtained for 65 MeV/nucleon at KVI were compared with theoretical predictions and revealed both a significant influence of 3NF [15,17] and Coulomb effects [16]. The data [15,17] confirmed the importance the 3NF for understanding of the 3N system dynamics. Inclusion of this additional force in the calculations leads generally to a better description of the cross-section data.

The other important and crucial piece of the dynamics turned out to be the electromagnetic interaction in some parts of the phase space. Only calculations which take into account both dynamical components, i.e., the 3NF and the Coulomb force, are able to remove disagreements between data and calculations. Adding the electromagnetic force into the calculations does not essentially change the quality of the data description at large relative energy (E_{rel}) of the two breakup protons. However at small E_{rel} values the observed discrepancies are almost totaly removed. The inclusion of 3NF and Coulomb effects into the calculations does not remove completely the disagreement between data and theoretical predictions. There are still some discrepancies at large E_{rel} which can be interpreted as indication that parts of the dynamics are missing, either relativistic effects or unresolved problems in our understanding of the 3NF structure.

The Coulomb force effects were studied in more details in a dedicated experiment at FZJ [18–20], focusing on a very narrow part of the phase space. This study was extremely important due to the fact that the electromagnetic interaction reveals itself quite strongly in this region. The results confirmed the importance of the Coulomb force and showed that only models containing the missing part of the dynamics reproduce the data in a proper way, see Fig. 1. To trace the influence of the electromagnetic processes globally, the dependence of χ^2 per d.o.f. was studied as a function of E_{rel}, see Fig. 2. The χ^2 was calculated as the squared difference between the experimental cross section value and the theoretical one and divided by the uncertainty of the

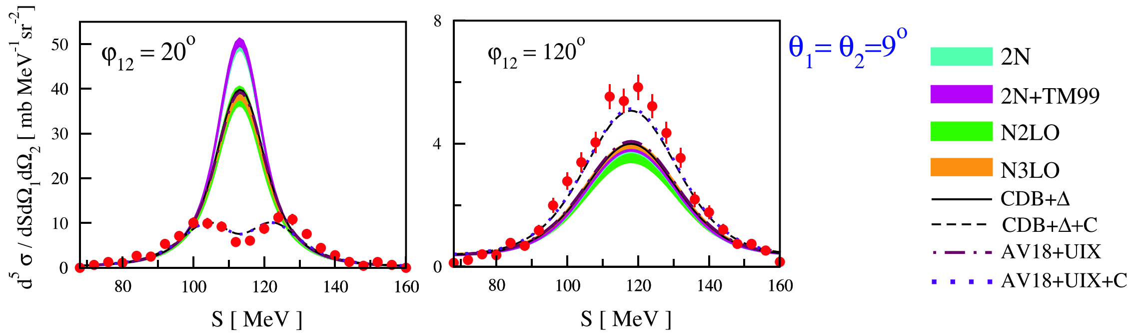

Fig. 1 Differential cross-section data for the $d-p$ breakup reaction at 130 MeV at two different kinematical configurations (specified in the *panels*) in which significant Coulomb force effects are observed. The data are compared to various theoretical calculations, described in the legend

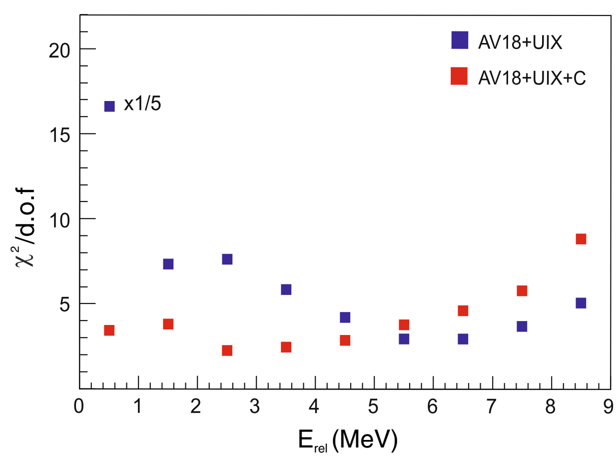

Fig. 2 Quality of description of the cross-section data with the calculations based on the AV18 NN potential combined with the Urbana IX 3NF (*blue squares*) and, in addition, with the Coulomb force included (*red squares*). The dependence of χ^2/d.o.f on the kinetic energy of the relative motion of the two breakup protons is shown. The point with a very large value of χ^2/d.o.f is scaled down by a factor of 1/5, as indicated in the *panel* (color figure online)

experimental datum. In the case of very small E_{rel} the Coulomb effects are extremaly high. For very large $E_{rel} > 5.5$ MeV the discrepancies are still present, but become much smaller. The results obtained revealed a quite strong influence of Coulomb force effects on the breakup reaction. It has been proven that only the predictions containing the Coulomb component are able to reproduce the data in a correct way. Figure 3 presents the seize of the predicted relative Coulomb effect on the cross-section data (relative difference of the results obtained with (σ_{th+eff}) and without (σ_{th}) the Coulomb force) as a function of E_{rel}. The effect is at the level of up to about 40 %.

The measurements provided a very rich set of data for the vector A_x, A_y and tensor A_{xx}, A_{xy}, A_{yy} analyzing powers as well. In this case the dynamics of the system was also investigated by use of the χ^2 and E_{rel} variables. For the A_x and A_y analyzing powers the χ^2/d.o.f. was analyzed as a function of E_{rel} (see Fig. 4). The results obtained at 65 [14] and 50 MeV/nucleon [13] are well reproduced by 2N calculations in the whole phase-space studied. This observation implies that the observables are practically insensitive to details of the nuclear dynamics. In case of the tensor analyzing powers [14] certain discrepancies are observed at 130 MeV. The theory predicts significant effects of the TM99 3NF. However there are configurations in which inclusion of the TM99 3NF leads to a worse agreement with the experimental data. Such discrepancies were found especially for the A_{xy} tensor analyzing power. This suggests that important ingredients are missing in the spin part of the 3NF model.

For the data [12] measured with the GeWall detector, the values obtained for A_x and A_y are very small and they do not reveal any interesting effects connected with the 3N dynamics. In general, the data confirm the theoretical calculations, though they can be described by the calculations limited to the pairwise NN interaction only.

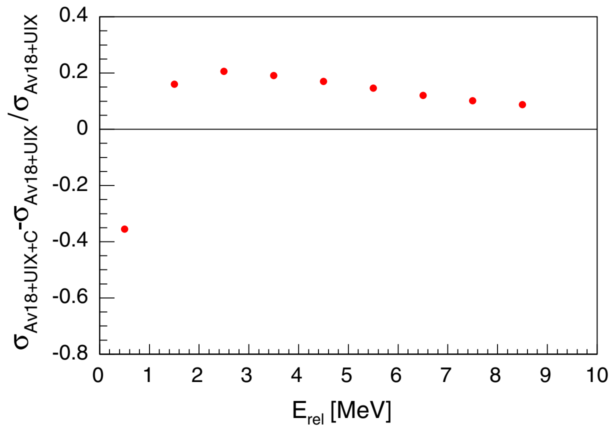

Fig. 3 Net effect of the Coulomb force on the theoretical breakup cross section at 65 MeV/nucleon presented as function of the E_{rel} variable. The calculations are matched to the acceptance of the GeWall detector

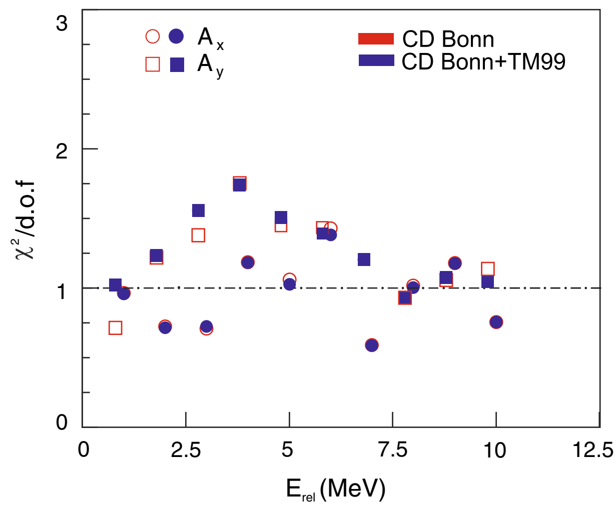

Fig. 4 Quality of description of the vector analyzing powers of the deuteron-proton breakup reaction at 50 MeV/nucleon given by various models (as indicated in the *panel*), presented as dependence of χ^2/d.o.f on kinetic energy of the relative motion of the two breakup protons (E_{rel})

4 Summary and Outlook

Precise and systematic studies of the breakup reaction in a large part of the phase space are very important for understanding of the interaction between nucleons in few-nucleon systems. Theoretical approaches, which try to model the interaction, need a very precise and large experimental database. The currently available database has to be verified and extended. Using the theoretical predictions different pieces of the dynamics can be studied separately and also their mutual interplay can be investigated. The data were obtained at several beam energies, and in general, they confirm the modern calculations. However there are still some problems with our understanding of the current models of the 3NF. Moreover, there is a strong need to have complete theoretical treatments, including all ingredients of the 3N system dynamics (3NF, Coulomb interaction, relativistic effects).

Recent years brought significant progress in the theory. The relativistic treatment of the breakup reaction in 3N systems was developed using NN potential in [8] and this approach has also been extended to calculations with 3NF effects in [9]. At higher energies only very scarce data for the breakup observables exist. The data are randomly distributed over the phase space and are not sufficient to draw any global conclusions concerning the influence of relativity or 3NF effects. To test the theoretical achievements an experiment was performed with the WASA detector at FZ-Jülich at deuteron beam energies of 340, 380 and 400 MeV. The results will enable the study of the evolution of relativistic and 3NF effects on the cross section at higher energies. This will put strong constraints onto the theoretical calculations and will allow to improve the quality of the existing few-nucleon potential models.

New experiments to study the 3N system dynamics are planned, including also investigations of the three-body system in the four-body environment. A new scientific program concentrated on the investigation of the few-nucleon systems dynamics at not too high energies was proposed to be carried out with the use of the BINA detector at the Cyclotron Center Bronowice in Cracow, Poland. This scientific center offers the possibility to continue the experimental program of investigation of the few nucleon systems dynamics with the use of proton beams in the energy range between 70 and 230 MeV.

References

1. Coon, S.A., Han, H.K.: Reworking the Tucson-Melbourne three-nucleon potential. Few Body Syst **30**, 131 (2001)
2. Pudliner, B.S., et al.: Quantum Monte Carlo calculations of nuclei with A < 7. Phys. Rev. C **56**, 1720 (1997)
3. Deltuva, A., Machleidt, R., Sauer, P.U.: Realistic two-baryon potential coupling two-nucleon and nucleon-Δ-isobar states: fit and applications to three-nucleon system. Phys. Rev. C **68**, 024005 (2003)
4. Entem, D.R., Machleidt, R.: Accurate nucleon–nucleon potential based upon chiral perturbation theory. Phys. Lett. B **524**, 93–98 (2002)
5. Epelbaum, E.: Few-nucleon forces and systems in chiral effective field theory. Prog. Part. Nucl. Phys. **57**, 645–741 (2006)
6. Deltuva, A., Fonseca, A.C., Sauer, P.U.: New calculations schemes for proton–deuteron scattering including the Coulomb interaction. Phys. Rev. C **73**, 057001 (2006)
7. Deltuva, A.: Momentum-space calculation of proton-deuteron scattering including Coulomb and irreducible three-nucleon forces. Phys. Rev. C **80**, 064002 (2009)
8. Skibiński, R., Witała, H., Golak, J.: Relativistic effects in exclusive neutron–deuteron breakup. Eur. Phys. J. A **30**, 369 (2006)
9. Witała, H., et al.: Three-nucleon force in relativistic three-nucleon Faddeev calculations. Phys. Rev. C **83**, 044001 (2011)
10. Stephan, E., et al.: Precise set of tensor analyzing power T_{20} data for the deuteron–proton breakup at 130 MeV. Eur. Phys. J. A **42**, 13 (2009)
11. Ramazani-Moghaddam-Arani, et al.: Elastic proton–deuteron scattering at intermediate energies. Phys. Rev. C **78**, 014006 (2008)
12. Ciepał, I., et al.: Vector analyzing powers of deuteron–proton elastic scattering and breakup at 130 MeV. Phys. Rev. C **85**, 017001 (2012)
13. Stephan, E. et al.: Vector analyzing powers of the deuteron–proton elastic scattering and breakup at 100 MeV. Eur. Phys. J. A **49**, 36 (2013)
14. Stephan, E., et al.: Vector and tensor analyzing powers in deuteron-proton breakup at 130 MeV. Phys. Rev. C **82**, 014003
15. Kistryn, St., et al.: Systematic study of three-nucleon force effects in the cross section of the deuteron–proton breakup at 130 MeV. Phys. Rev. C **72**, 044006 (2005)
16. Kistryn, St., et al.: Evidence of the Coulomb-force effects in the cross sections of the deuteron-proton breakup at 130 MeV. Phys. Lett. B **641**, 23–27 (2006)
17. Kalantar-Nayestanaki, N., et al.: Signatures of three-nucleon interactions in few-nucleon systems. Rep. Prog. Phys. **75**, 016301
18. Ciepał, I., et al.: Studies of the three-nucleon system dynamics in the deuteron–proton breakup reaction. EPJ Web Conf. **37**, 09011 (2012)
19. Ciepał, I., et al.: Investigations of few-nucleon system dynamics in medium energy domain. Few Body Syst. **601**, 1–5 (2013)
20. Kłos, B., et al.: Systematic studies of the three-nucleon system dynamics in the deuteron–proton breakup reaction. Acta Phys. Pol. B **44**, 345 (2013)